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PASSIVE SOLAR SPACE HEATING*

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ABSTRACT

An overview of passive solar space heating is presented indicating trends in design, new developments, performance measures, analytical design aids, and monitored building results.

1. INTRODUCTION

The purpose of this plenary paper is to provide an overview of the state of the art in passive solar space heating applications, indicating lessons learned in the last year or so, trends in passive solar space heating applications, on-going research which will increase the potential use of passive solar, and the results of performance evaluation of some monitored buildings.

Passive solar space heating is, at the same time, a very new and a very old use of the sun's heat in buildings. We are all very familiar with applications dating back to prehistoric Indian tribes in the American Southwest, traditional building types in the Middle East, and the passive solar houses of the Keck brothers in the 1930's in the Midwest.

The difference that I see in the last three or four years is one of intensity and diversity. The tools of modern engineering analysis are being applied to the problem in a methodical and effective manner providing everything from rules of thumb to simplified methods of analysis to sophisticated computer-based solutions. New high technology materials are being developed. We have become relatively sophisticated in looking at the building in a holistic sense, striving to provide a minimum requirement for outside energy sources while maintaining maximum comfort standards, a maximum reliability and predicted longevity, all at a very small add-on cost. Considerations of comfort, aesthetics, livability, resalability, minimum net energy impact, and marketing are all brought into the equation. We worry about such things as optimizations brought into play by government economic incentive programs. We are concerned in showing compliance with proposed Building Energy Performance Standards. We are annoyed about definitional issues.

Such symptoms are not a sign of problems with passive solar applications; rather they are indications of a maturing field in which great progress is being made.

The most important indicator of progress is the overwhelming degree to which passive solar has been endorsed by builders and buyers who, not knowing what a Trombe wall was a year ago, now covet one.

It used to be difficult to find good passive solar examples; now they are proliferating everywhere. Small enclaves of passive solar enthusiasts abound in sun starved regions as well as sun blessed areas.

Another indicator of the fact that passive solar is fashionable is in its endorsement by virtually all government programs, at all levels (with the notable exception of the IRS). DOE funding has increased from $130,000 in 1974 to $18,300,000 in the 1980 fiscal year.

2. TRENDS IN PASSIVE SOLAR HEATING

The design of passive solar buildings has evolved rather quickly from the simple, well-known prototypes of direct gain (the Wright house in Santa Fe), thermal storage wall (the Trombe-Michel house in Odeillo), water wall (the Baer house in Albuquerque), attached solar sunspace (the Yanda style add-on solar greenhouse or Nichol's Unit 1

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in Santa Fe), thermal storage roof (the "Skytherm"[R] Atascadero house by Hay), and thermosiphon or convective loop (thermosiphon water heaters or the thermosiphon air house of Davis in Albuquerque).

These notable buildings have served as good examples to describe the concepts. However, thousands of new passive solar buildings have been designed and built in the interval between 1975 and 1980 and these embody a large number of notable design trends. These combine the best characteristics of the basic system types into mixed or more advanced designs which overcome some of the disadvantages of the basic types. They tend to be more livable and effective while not necessarily increasing the cost.

2.1 Trends in Direct Gain

The original "Sunscoop" house by David Wright in Santa Fe has served admirably as an example of the direct gain principle. The building is the epitome of design simplicity. However, it also serves to illustrate some of the difficulties which can be encountered when direct gain is used to excess. The entire south side of the house is double glazed and the amount of sun entering during a typical sunny New Mexico winter day is overpowering. The entire inside of the house is bathed in sun and some of the problems which can arise in direct gain are very evident: ultraviolet degradation of fabrics and other materials, strong side lighting and glare, "fishbowl" living, and a temperature swing on clear winter days of 20 F despite the enormous amount of thermal mass in the back and side walls and in the floor. However, the house does use very little backup heat.

The evolution of the use of direct gain by Wright and other designers now shows a much more sophisticated approach. Glazing is used in smaller quantities more uniformly distributed throughout the building. This allows a better distribution of excess solar heat to heat-storing mass and a better geometrical relationship of the two.

The use of clerestory windows has become popular. This allows for a better distribution of both solar radiation and natural daylight throughout the building. In some cases a repetitive sawtooth roof design is used. The north wall of the building becomes effective for heat storage and light is brought into the northern rooms.

Another approach is the use of diffusing instead of clear glazing. This scatters the incident sunlight to various angles more uniformly heating the space and more uniformly lighting it. An early use of this is in the Wallasey School in Liverpool, England built in 1962. This is an example of a building in which the primary benefit is in the reduction of energy for artificial lighting by the substitution of natural daylight. The passive solar heating is largely balanced by the increased thermal losses through the large glazing area resulting in a solar savings which is relatively small. Nonetheless the "solar heating fraction" is unity since the backup heat is generally zero. This is possible because the amount of energy released by the students' body heat, the remaining artificial lighting, and the sun is sufficient to maintain building comfort.

A problem with diffusing glazing used on the south wall is glare. The most successful applications of diffusing glazing have been in clerestories used in conjunction with a white ceiling interior to provide a large soft source of overhead light.

Another trend in direct gain is the use of blinds located behind the window to reflect incident sunlight toward the ceiling of the building. The classic example is the MIT 5 house in which the blinds are of a thin Levolor type located between the double glazings. A reflective mylar coating is located on the concave upper side and can be adjusted to provide a uniform wash of light across the ceiling.

Another application of the same approach is being made in a lab building at the Oak Ridge National Laboratory. Here the blinds are made of specially contoured wooden slats with a reflective surface on the concave upper side. The slats can be turned to close completely providing some degree of night insulation or totally blocking the incoming sunlight.

Perhaps the most exciting trend in direct gain is the evolution of coatings for glazings to reduce the overall heat loss coefficient. "Heat mirror[R]" coatings have been developed which reflect infrared solar radiation back into the room. Other infrared coatings have been used in Europe, located on the outside surface of the inner glazing. The advantage of this location is that the inner glazing operates warm and thus the tendency for condensation is reduced. The coating reduces the emission of infrared radiation from the inner glazing toward the outside. The infrared coatings can also be located on a film located between double glazings. Heat loss coefficients as low as 0.25 Btu/F-hr-sq ft have been reported for the assemblies.

Of course such coatings also reduce solar penetration through the glazing; the effect may be to reduce the overall transmittance by 10 percent. This is probably an acceptable penalty when balanced against the reduced heat loss since it is the net thermal performance of the glazing that is important.

Some authors have even suggested that we can look forward to the use of glazings on all orientations, north included, in advanced passive solar designs.

2.2 Trombe Walls

Trombe walls are usually built either of poured-in-place concrete or of masonry units such as concrete blocks (with the cores filled), brick, or adobe earth brick. Concrete is preferable because of its higher thermal conductivity and higher density but all are acceptable.

A major design consideration is whether or not to use thermocirculation vents in conjunction with the Trombe wall. Omitting the vents reduces complexity in design and construction, avoids problems caused by dirt and insects in the space between the wall and the glass, and gives a greatly increased thermal stability of the building (reduced temperature swings). Many designers prefer not to use the vents.

The primary function of the thermocirculation vents is to provide heated air to the space during the day. In many applications this is simply not appropriate. In others it might better be done by the use of direct gain than by thermocirculation. In residential applications the primary heating is desired in the evening and the unvented Trombe wall provides this very effectively. Direct gain can be used to provide daytime heating by sizing the direct gain windows to be equal to approximately one-third of the total solar wall, with the other two-thirds being Trombe wall.

Another development in Trombe wall design is the use of a selective surface on the outside of the wall. Since a major mechanism of energy loss through glazing is by radiation flow, thermal losses are greatly reduced by decreasing the infrared radiation from the Trombe wall surface by the use of a material which has a low thermal emittance. Black chrome selective surfaces are now available on metal foil which can be glued to the wall surface having a solar absorptance greater than 94 percent and a thermal emittance of less than 10 percent.

Tests done at the Los Alamos Scientific Laboratory indicate that performance is greatly enhanced by the use of a selective surface on either a Trombe wall or water wall configuration. Performance improvement is comparable to that achieved using night insulation. Recent results indicate quite satisfactory performance when selective surfaces are used in conjunction with single glazing, in agreement with analytical predictions.

Quite a few variations on the Trombe wall approach are being utilized. These include half-height walls with windows above, the vertical louvers used by Bier, and various other interesting masonry shapes located behind the glazing.

Sometimes sand has been used as the fill in concrete blocks used in Trombe walls. This is unfortunate because it is very poor from a thermal performance standpoint. The sand will soon become very dry and have a very low thermal conductivity due to the many air gaps surrounding the sand grains.

2.3 Water Walls

The primary advantage of the water-wall approach is the ability to obtain very large thermal storage in a reasonable space.

Virtually every size and shape of water container has been used in water walls. Metal culverts (spiral Grecian columns) have been used by Hunt and others in Davis, California, welded to steel plates in the floor in order to satisfy California seismic codes. Conventional containers of all sizes and shapes have been stacked. Vertical fiberglass reinforced acrylic tubes made by Kalwall are widely used. Special containers, designed to be nested for shipment, have been built of fiberglass by Maloney. A "heat wall®" concept has been designed by Nichols. It is a sheet metal tank designed to be slipped as a modular unit between 2" x 12" studs on four foot centers.

In many instances attempts have been made to provide a normal-looking interior to the building rather than the unusual effect created by water bottles, oil drums, vertical tubes, or other forms. In such cases a reasonable thermal bond must be established between the interior panel and the water storage container or a decrease in annual performance of 5 to 10 percent will result.

As mentioned above, selective surfaces can also be used on the external side of a water wall in order to obtain significant performance improvement.

2.4 Attached Sunspaces

Perhaps the most significant trend in passive solar design is in the popularity of the attached sunspace. The simple add-on solar greenhouse pioneered by Bill Yanda has spread in the thousands to virtually every part of the country. Various shapes are used to achieve different effects and to adapt the sunspace to various climates.

Frequently the sunspaces are retrofits to existing buildings providing additional heat to the house as well as an additional space which can serve recreational or functional purposes or provide a greenhouse in which plants can be raised throughout the year without the need of auxiliary heating.

One trend has been toward very-low-cost greenhouses generally built by the homeowner. Simplicity and economy are the primary objectives. Simple timber framing is used for the structure and either UV inhibited fiberglass reinforced acrylic or flexible plastic materials are used for the glazing. Materials costs of less than $5 per square foot of greenhouse space are often quoted.

Other greenhouse designs have incorporated more costly use of wood mullions and glass in structures which become a definite aesthetic asset to the building.

One difficulty in providing performance estimates for attached sunspace configurations is the large variety of geometries which are possible. Two particular geometries have been studied by McFarland and Jones in another paper within these Proceedings.[1] Solar Load Ratio correlations are given for these cases. Both geometries are linear attachments of a sunspace along the south side of a building. The interesting result is that the performance characteristics of one of these sunspaces is comparable to or slightly exceeds the performance characteristics of a Trombe wall having the same glazed area. It seems that the additional losses in the greenhouse associated with roof and end walls are approximately compensated by the fact that the glazing is tilted at the optimum angle. One also achieves a greater surface area of heat-storing mass because of the floor of the sunspace in addition to a mass wall separating the sunspace from the attached building.

The "wraparound" greenhouse design pioneered by the Nichols in Unit 1, First Village[2,3] has been a particularly successful and widely adopted approach. The thermal advantage of the design is that there are no end wall losses on the east and west since the building borders the sunspace on those sides. This has the added advantage of blocking east and west solar gains in the summer reducing the tendency that most greenhouses have to overheat.

A notable trend in attached sunspaces is the incorporation of a rock bed for heat storage. Since the air is normally fan forced, its inclusion results in the design being a hybrid. However, the coefficient of performance (defined as the ratio of heat energy transported to the electrical energy required to run the fan) is typically about 8 to 12 in such applications. Since this heat energy might otherwise be lost either due to overheating or venting, the high coefficient of performance largely justifies the use of external energy and the complication of the system design.

The most typical configuration is the use of a system of air ducts, a fan or blower, and a rock bed. The rock bed is an excellent heat exchanger and is low cost and relatively simple to construct. Obtaining suitable rock is not always easy. The advantages of the fan-forced rock bed approach are that it provides a means of reducing the daytime temperatures in the greenhouse (which would otherwise frequently tend to overheat on sunny winter days), saving that heat for a later time, and transporting the heat from the upper south part of the building to the lower north part of the building (frequently underneath the floor). The preferred approach is to design the rock bed for active charging (using the fan) but passive discharge by conduction into the heated space either up through the floor or inwards from a wall. By making the barrier between the rock bed and the heated space of thick masonry construction (such as a floor slab), increased thermal stability, a delay in the arrival of the heat into the space, and additional heat storage are all obtained.

A potential problem with the rock bed approach is the possibility of fungus or other growth within the rock bed. This has not not been reported to be a problem but has not been thoroughly investigated. Further investigation would be appropriate.

A primary advantage of the sunspace approach is the variety that it offers in the building design. A sunspace can be used as an atrium or conservatory, as a hallway or transit area, as an airlock entry, or, of course, as a greenhouse. It is increasingly being used in commercial buildings as a large and attractive entry foyer or as an element in a scheme of natural daylighting.

2.5 Trends in Thermal Storage Roofs

The original concept of the roof pond developed by Hay is particularly effective as a cooling system in the summer in a climate which requires only modest amounts of heating in the winter. Problems encountered in the design have been primarily associated with the mechanism of movable insulation. Some variations in the design have been made which incorporate insulation floating within the roof pond, with the water being pumped to the top of the insulation during winter days or summer nights.

Analyses done by Trinity University in Texas have indicated that the performance of the roof pond should be acceptable over a wider range of climatic conditions than had originally been supposed.

Another variation of the roof pond approach is the "Cool Pool[R]" concept developed by the Living Systems Group in Davis, California. Here the roof pond is used entirely for cooling by erecting a sunshade over a flooded roof configuration. Energy from the building is thermosiphoned to the roof passively up tubes which extend to the floor level. Experimental results have shown very significant decreases in water and building temperatures compared to average ambient conditions.

Other variations in the thermal storage roof are the use of the "Skytherm North[R]" concept by Hay in which water bags are placed between the roof rafters and glazing is utilized on the south-facing pitch of the covering roof. Saunders has used water in large glass carboys in a similar glazed attic space.

The Los Alamos Scientific Laboratory has experimented with the thermal storage roof in a design intended for use in mobile modular housing. Monitoring of the building over a winter indicates that the useful solar heat is 80 percent of the net thermal load.[4]

One application which would seem to be quite suitable for roof ponds is in large concrete commercial structures where the advantage of the roof pond in summer cooling would be utilized.

2.6 Trends in Convective Loops

The enormous advantage of the passive thermosiphon water heater is slowly being realized in the United States. Tens of thousands of these units are in routine service in Israel, Cyprus, and Australia. Tests by three major testing laboratories in the United States (the Bureau of Standards), New Zealand (the Division of Scientific Industrial Research), and in Australia (the Commonwealth Scientific and Industrial Research Organization) have all indicated that passive thermosiphon water heaters outperform their active counterparts. Water heaters manufactured in the countries cited above cost between one-third and one-half of the standard active water heaters sold in the United States. These advantages of the thermosiphon water heater are so compelling that it would seem appropriate to look for ways to incorporate them into American buildings despite the obvious institutional problems.

Another passive solar water heating concept which should not go without mention is the batch heater or tank type system. This is basically a direct gain approach. Variations on this theme utilizing several tanks have shown good results.

Returning to the subject of space heating, the thermosiphon air approach has been used in a few buildings. The Mark Jones hybrid system in Santa Fe has been monitored and shown to have good performance. A few other air thermosiphon buildings have been constructed. One trend has been toward a design in which the rock bed storage is coupled passively to the building and located within the building. This has been done both in underfloor rock bed storage and in rock beds built within walls of the building. The approach seems to be effective but suffers from the necessity of placing the collectors low relative to the heat storage. This restricts the use of the concept to sites where this is practical. Another possibility, of course, would be to build the building well above ground, that is, on stilts. While this approach to building design is not common in the United States it is employed frequently in some countries.

One of the most important developments in convective loops is the use of a lightweight convective air heater to provide warm air to the building during the day. This is a particularly attractive option in retrofit of existing buildings since it can be employed at relatively low cost simply by attaching the convective air heater to the south wall and cutting two vents through the wall. For good performance it is necessary to prevent reverse thermosiphoning at night. A variety of such convective units have been built and shown to be give quite satisfactory performance.

2.7 Trends in Movable Insulation

The use of some kind of insulation assembly which can be placed on the solar glazing at night to reduce heat losses can greatly improve performance. Several new passive solar products have emerged on the market to provide such movable insulation. Most of these are roll-down assemblies which are located inside the building. The added R value of the insulation varies from 5 to 15.

An advantage to placing the movable insulation system inside the window is that it is in a protected environment and thus the assembly does not have to withstand the rigors of the outdoor weather. Another advantage is that the air infiltration through the assembly is not nearly as great inside since the effects of outside winds are not encountered. A significant problem with inside location, however, is condensation and possible freezing of water vapor on the resulting very-cold glass surface of the window. An excellent seal must be made or this will become a major problem, especially in a particularly cold and humid climate.

Locating the insulation outside the glazing has the advantage that the glazing thereby runs warm and condensation is not a problem. Unfortunately outside shuttering systems commonly used in other countries are not traditionally employed in the United States and the cost of such systems here is presently quite high. Furthermore the outside shutters which have been built have not been designed from the point of view of obtaining good insulation value and performance is relatively low. I expect that the trend in movable insulation will be toward outside assemblies which are designed to be thermally effective.

3. PERFORMANCE MEASURES

One objective of passive solar design is to reduce the dependence of the building on conventional sources of heat from a furnace or even an active solar system. The most important measure of performance is therefore the annual auxiliary heat required to maintain a particular desired minimum temperature within the space.

Of course, the auxiliary heating requirements can also be reduced by energy conservation measures such as better insulation and reduced infiltration. There has been some controversy between those who advocate super-insulated buildings and those who prefer a passive solar approach. In fact, extremes in either direction are likely to lead to a building which is less satisfactory than a mixture of strategies. The optimum mix between passive solar and energy conservation is discussed in another paper within these Proceedings.[5] This paper provides a methodology for determining the minimum initial cost required to obtain a given desired minimum level of auxiliary heating. The net effect is to provide a building which is more open to its environment than the super-insulated house and less subject to the extremes of a "solar heated barn". Most designers of passive solar homes are quite conscious of the necessity for good energy conservation and intuitively tend to designs which are relatively close to the optimum mix.

Both designers and owners of solar systems have always been keenly interested in one particular performance measure -- the "solar fraction". Ambiguities in defining the solar fraction have plagued all solar system designers but this has become an especially important issue in passive systems. The problem has been well discussed by Palmiter.[5] The distinctions, which seem rather subtle at first, become important when it is realized that relatively large differences can result.

A Solar Heating Fraction can be defined in a variety of ways, and this has been one of the problems with its use. The numerator could be either the net or gross solar contribution and the denominator could be either the actual building thermal load or the thermal load of the same building but held at a steady reference temperature. These problems in usage have led to the abandonment of the Solar Heating Fraction as a performance measure and its substitution by the Solar Savings Fraction.

It is convenient to define the Solar Savings Fraction as the ratio of the solar savings to a reference load defined as the amount of energy required by the comparable non-solar building. This reference load is just equal to the amount of auxiliary heating which would be required in the conventional non-solar building and therefore does not include that portion of the thermal load which is supplied by internal sources of energy (such as people heat, energy from appliances, and lights). Thus the Solar Savings Fraction (SSF) is defined as follows:

$$SSF = 1 - \frac{\text{auxiliary heating in solar building}}{\text{auxiliary heating in non-solar building}}$$

A particular advantage of the Solar Savings Fraction approach is that it leads directly to auxiliary energy use through the equation:

Auxiliary = (1-SSF) x (net reference load) where the net reference load is the heat required by a conventional non-solar building.

Minimizing auxiliary energy usage is only one criteria of good passive solar design. Another is to obtain good comfort characteristics in the building. This means maintaining temperature variations within the building to an acceptable level. These temperature variations tend to be largest during sunny weather when the change from day to night tends to be the greatest. This is an important design parameter and is called the winter clear-day temperature swing. This temperature swing is affected by the amount of solar glazing, the type of passive system, the amount and effectiveness of thermal mass, the thermal losses of the building, and the latitude of the site.

4. ANALYTICAL DESIGN AIDS

It is useful to catalog design aids according to when they would be used during the evolution of the building design. A complicated analysis which would be appropriate during the later phases of the design would be entirely inappropriate during the initial phases. This hierarchy of design aids, intended to fit comfortably within the design process, is shown on the following chart.

Design Phase	Design Aid
Schematic Design	Rules of Thumb
Design Development	LCR Method
Construction Documents	Monthly SLR Method

Each of the design aids is discussed below. It is also possible to use simulation analysis as a design aid and this will also be discussed.

4.1 Rules of Thumb

During the schematic design phase the most useful information the designer can have are rules of thumb. These rules are of two types: patterns and numerical ratios.

Patterns are special principles which are incorporated into the design which lead to good thermal performance. Examples are the use of an airlock entry to reduce infiltration, placing of closets and other such spaces on the north side of a building to reduce thermal losses, and elongation of the building in an east-west direction to maximize the potential for winter solar gain and minimize problems of summer overheating. These patterns have been enumerated and discussed by Mazria.[7]

The numerical rules of thumb provide an indication of appropriate sizing criteria for solar glazing, thermal mass, and orientation. Such rules have been given by Mazria[7] and also by Balcomb in a separate paper in these Proceedings.[8]

The rule of thumb for sizing solar glazing is the most important and is given as a ratio of the solar glazing area to the floor area of the building. In order to do this an assumption is made as to the degree of energy conservation. One can adjust the ratio up or down if a lesser or greater degree of energy conservation is actually employed.

4.2 The Load Collector Ratio Method of Estimating Annual Performance

The single most important variable which characterizes the effect of building design on annual performance is the Load Collector Ratio. This ratio is defined as follows:

$$LCR = \frac{\text{Building Heat Loss Coefficient}}{\text{Solar Glazing Area}}$$

In Imperial units the building load coefficient is normally given in Btu/F-day (sometimes abbreviated Btu/DD or Btu per degree day) and the solar glazing area is given in square feet.

The LCR is important because it relates the load characteristics of the building to the total solar-collecting aperture. If one thinks of the solar aperture as replacing (in a seasonal sense only) the furnace in the house with solar glazing, then the LCR relates the heat demand characteristics of the building to the heat supply characteristics. The LCR reveals this balance in one simple ratio.

For a particular climate and passive system type the annual SSF can be directly related to the LCR. Tables have been generated which give this relationship for 219 sites around the U.S. and southern Canada.[9]

The LCR method provides a technique whereby the designer can quickly assess the implications of design decisions made during design development to their effect on thermal performance.

Other aids useful during design development are sensitivity curves. These show the effect on performance of changing any of the parameters of the reference design, such as Trombe wall thickness, orientation, or thermostat setting. Many such sensitivity curves are given in Ref. 9.

4.3 Detailed Estimates for the Construction Documents Phase

The main purpose of the thermal analysis in the construction documents phase is to confirm that the building will meet criteria. More detailed account is taken of the building thermal loss and the solar gain characteristics on a monthly basis, accounting with more precision for the effects of angles, shading, and actual sizes of spatial relationships. The monthly reduction in auxiliary heating due to solar is estimated for average weather and solar conditions in the area. Clear-day temperature swings are also estimated with more detail.

A procedure for doing these detailed estimates is given in Ref. 9 based on the use of the LASL Monthly Solar Load Ratio method. Although more complex than the LCR method, the technique can still be done by hand and a methodology is described which leads the designer through the process using tables which are filled in on a monthly basis.

During the final phase of design, it is also desirable to do a detailed estimate of the building temperature swing in cases where this may be a problem, such as when a large amount of direct gain is used. Ref. 9 provides an estimating procedure which will yield appropriate answers which account quantitatively for the important physical effects: thickness and material properties of the thermal storage materials, location of these materials, and orientation of the surface. The technique can be carried out by hand using tables provided.

4.4 Simulation Analysis

Simulation analysis consists of representing the physical system by a set of mathematical equations which account for the flow of heat between various locations within the system and the storage of heat energy by various massive elements. Passive systems have proven to be quite accurately represented by relatively straightforward and simple simulations. The techniques which were utilized to generate the Solar Load Ratio correlations and the LCR tables are based entirely on multiple year-long simulation analyses done for a variety of climates.

The question is: Should simulation analysis itself be used as a design tool? The problem is that a normal design office, such as an architectural or building engineering firm, is generally not able or willing to support both the cost of the equipment and specialized personnel to do this type of analysis. However, the situation is changing and the advent of inexpensive desktop microcomputers presents an intriguing option for these designers. These machines are very powerful and easily capable of a very respectable simulation analysis. Computation time is moderately long, compared to a large computer, but quite acceptable to an operator studying one or two week weather periods. A host of solar geometry and other fast routines can be packaged to provide quick information access useful during design development. The whole process can be made simple, interactive, and fun.

In the meantime the hand techniques, based on the correlation analysis such as the Solar Load Ratio method, will serve as a useful and accurate basis for design estimates. For standard configurations they will probably always be the preferred method.

The power of the simulation technique is so great and so compelling that it ultimately will be the preferred approach among some designers. It is better suited to cope with the variety of design approaches which may be encountered.

A variety of simulation codes have been developed. These include PASOLE (Los Alamos Scientific Laboratory), DEROB (University of Texas at Austin), SUNCAT (National Center of Appropriate Technology), and UWENSOL (University of Washington). These codes are all based on the simulation analysis approach (also called the thermal network method).

Other computer codes which might be used for design are the large building thermal load programs. These are based on the thermal response factor method of analysis which is not particularly well suited to describe passive solar heat flow. However the largest of these codes, DOE-2, is being adapted to incorporate passive solar concepts. This will be most suitable for use in very large buildings which incorporate a large amount of heating ventilating and air conditioning equipment but incorporate some passive solar gains.

In such large buildings, however, the major design issue is the use of natural daylighting to reduce the requirement for artificial lighting and the associated air conditioning loads associated with such lighting. The detailed analysis of natural daylighting techniques is very difficult and designers will probably rely on rules of thumb backed up by scale model studies.

5. PERFORMANCE EVALUATION OF MONITORED BUILDINGS

The popular conception is that the evaluation base for passive solar buildings is very scant. By comparison with active solar systems this is undoubtedly so, but there does exist a significant evaluation base based on observations made in passive solar buildings over a period from 1969 to the present time. A few buildings were reported at the First and Second DOE Operational Results Conferences.[10,11] It is interesting to note that the best performances quoted at both of these conferences were for passive solar buildings. In addition there is an extensive literature on passive solar buildings contained primarily in the proceedings of the four National Passive Solar Conferences which have been held and the passive solar sessions at the annual meetings of the American Section of the International Solar Energy Society.

I have not made a comprehensive search to catalog all of the information available for all passive buildings. A brief search provides the information which is contained in Table I giving a few figures of merit. The column headings give various appropriate values defined as follows:

SHF. Solar Heating Fraction. The contribution of the total building load which is supplied by solar energy, computed after the effect of normal internal energy sources such as lights and people have been accounted.

Efficiency. The fraction of the total solar radiation incident on the collection wall which is ultimately delivered to the house as a useful contribution to the heating load.

Temperature Swing. The peak-to-peak temperature range observed inside the passive solar building during sunny weather conditions.

Solar Contribution. The annual amount of heat delivered from the solar wall to the structure, Btu/yr-sq ft.

Solar Savings. The total amount of heating energy which is saved by the presence of the solar wall. The comparison here is with a conventional construction on the south side instead of the solar wall and with the building held at the same comfort level.

5.1 Overall Evaluation.

It is clear that passive solar construction is thermally advantageous and questions pertaining to factors such as comfort, other livability considerations, and cost need to be evaluated building-by-building. Properly done, it appears that passive solar buildings can get high marks on all the evaluation criteria. There are many examples, however, where one or another factor leaves something to be desired. A comprehensive evaluation of a large sample of buildings against all criteria has yet to be done. Such an evaluation will be difficult, lengthy, and expensive.

Results from buildings which have been monitored indicate performance which equals or exceeds the estimates obtained by simulation analysis. However in these cases the largest unknown is the actual building load; expected performance is extremely sensitive to thermostat setting. Some owners prefer to accept a lower thermostat setting in order to obtain an 85% solar fraction rather than a more conventional thermostat setting which would lead to a 50% solar fraction. However this is decreasingly so as more and more passive solar buildings are occupied by people who did not build them.

The general consensus, based on feedback from hundreds of passive buildings located all over the United States, is that passive solar performance generally exceeds expectations. Annual heating costs of $100 per season or less are commonly reported for moderate-sized passive solar buildings even in cold climates. Such results are certainly influenced by a variety of psychological and physiological factors. Some passive home dwellers (especially in the first generation) adapted their lifestyles slightly, preferring a sweater to a normal thermostat setting, but this is becoming the exception rather than the rule. Most passive homes are now sold on the speculative market to buyers who are not necessarily solar advocates and it is both inaccurate and a poor strategy to market a passive solar house on the basis that any sacrifice in comfort is implied.

There is a growing body of evidence that correctly designed passive solar buildings have comfort characteristics which equal or exceed their non-solar counterparts. This is thought to be due to several subtle physiological factors. The most important of these is the effect of the thermal radiant environment on comfort. A second effect which enhances overall comfort is the incredible thermal stability of a well-insulated building with a large internal thermal mass.

In conclusion, the early results are very encouraging but continuing work needs to be done monitoring performance of actual passive solar buildings against a wider range of evaluation criteria.

TABLE 1 RESULTS FROM A FEW MONITORED PASSIVE BUILDINGS

	SHF	Eff.	Temp. Swing	Btu/sq ft-yr Solar Contribution	Solar Savings
Wallasey School	100%		7-16°		Nil
Trombe - Michel House	70%	36%			
Atascadero (Hay) House	(100%)*		2°		
Balcomb House	89%	37%	5°	189000	118000
Mobile-Modular II	80%	24%	10°	214000	78000
MIT 5	70%				
Fowlkes House	85%				
Kelbaugh House	80%		15°		
Hunn House	80%				
Hamilton College	68%				
Green Mountain Home	39%			90000	
Saskatchewan House	73%		11°		105000
Hullco**	100%	25%	5°		73000
Colorado Sunworks**	76%	38%	6°		93000
Kalwall Warehouse**	58%	43%			54000
Spence - Urban**					
Greenmoss**					Negative
Living Systems				81000	
Lumsdaine House	75%				
NMSU Skytherm[R]			2°		

* Data missing for two months in winter.

** Monitored under the National Solar Data Program.

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